PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Adaptive Closed Loop Control

We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America (assignees of RALPH ERNEST CLARRIDGE) do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates generally to control systems and particularly to those which adapt themselves to changing conditions in the system under control.

The gain adjustment of process controllers represents a compromise between system stability and rapid response to changes in the controlled system. A deviation of a controlled variable from a desired value, or set point, produces an error signal to the controller. If the controller gain is set to a high value, a small error will induce a large corrective action in a direction to restore the controlled variable to the desired value. If the gain is set too high, the corrective action will be excessive and the controlled variable may go beyond the desired value and cause the system to oscillate.

As an alternative, the controller gain may be set to a low value. If this is done, the control action will be sluggish and ineffective. In addition, the controlled variable will not be held close enough to the desired value under different load conditions. Therefore, the controller gain is normally set at a compromise value in which the control action is such that oscillations caused by control action tend to decay reasonably rapidly under all load conditions. Even this type of tuning, where the controlled gain remains constant, is not satisfactory for many applications since the maximum controller gain is limited to the value which provides stable operation over the entire range of the process.

Of course, if the operator is available to readjust the controller gain each time the process changes, the foregoing problem can be eliminated. In the usual case the operator does not have sufficient time for such adjustments and the compromise setting must be accepted.

Many processes and sensors which provide the input signals representing the value of the controlled variable are non-linear. In addition, the device which responds to the controlling variable, and which governs for example the admission of a medium such as steam or water, is often non-linear. Therefore, the gain setting which is satisfactory for one load condition is often unsatisfactory for another. One solution to this problem can, in suitable cases, be to make the gain adjustment of a function of the position of the valve or other device under control of the controller and therefore also a function of the load. As the valve reaches a point where the system can become unstable, controller gain may be reduced by means of a cam and follower arrangement associated with the valve. An obvious shortcoming in this system is the special tailoring required for the cam.

A large number of control problems require the use of a dual mode controller having both proportional and integral response. In such a controller, the control action is proportional to the error signal in the first instance, and additionally, to the time integral of the error signal. In such controllers, the integral term operates to increase the overall gain of the controller for very low frequency disturbances. A signal representing the integral term is commonly obtained by means of a high impedance integrating circuit including a capacitor. The environ-

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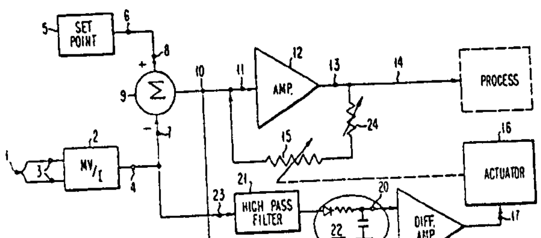

FIG. 1

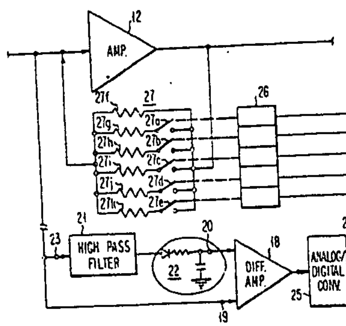

FIG. 2

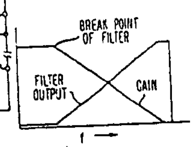

FIG. 4

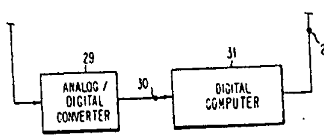

FIG. 3

mental and other shortcomings of high impedance circuits are well known.

According to one aspect of the invention, there is provided a method of adaptive closed loop control in which controller gain is varied in accordance with a gain control signal derived by subtracting a second component from a first component, the first component being or representing the error signal and the second component increasing with increasing rate of change of the error signal or the controlled variable, whereby the controller gain is varied in direct proportion with the magnitude of the error signal and in inverse proportion with the rate of change of the error signal or the controlled variable so as to give proportional plus integral control.

According to another aspect of the invention, there is provided an adaptive closed loop control system having a controller whose gain is varied in accordance with a gain control signal generated by error modification means, said error modification means generating said gain control signal by subtracting a second component from a first component, the first component being or representing the error signal and the second component increasing with increasing rate of change of the error signal or the controlled variable, whereby the gain control signal varies the controller gain in direct proportion with the magnitude of the error signal and in inverse proportion with the rate of change of the error signal or the controlled variable to cause the system to provide proportional plus integral control.

In two of the embodiments described hereinafter, to achieve an adjustment of controller gain in direct proportion with the rate of change of the error signal, an approximation is used. The rate of change of the error signal is determined by an analysis of either the controlled variable signal or the error signal. A high pass filter, which blocks the low frequency components of the signal and passes the higher frequency components, is used to extract a signal representing rate of change of the controlled variable. This signal is compared with the error signal, and the controller gain is then adjusted in accordance with the comparison.

The invention will now be further explained by way of example with reference to the accompanying drawing in which:—

FIGURE 1 is a schematic drawing of one embodiment of the invention;

FIGURE 2 is a schematic drawing of a portion of another embodiment of the invention;

FIGURE 3 is a schematic drawing of a modification to the embodiment of Figure 2; and

FIGURE 4 is a graph illustrating operation of the embodiments of Figures 1 and 2.

In a dual mode (i.e. proportional plus integral) controller according to this invention, it is preferred that the manipulation of controller gain follows the equation.

$$G = K\left(1 + R\left|\frac{(x-x_0)}{\frac{dx}{dt}}\right|\right)$$

where:

G is the gain of the controller;

K is a predetermined minimum gain of the controller;

R is the reset rate, (repeats per minute);

x is the controlled variable;

x_0 is the set point;

dx/dt is the rate of change of the controlled variable;

$(x-x_0)$ is the error signal.

From this relationship it can be seen that the gain of the controller will vary proportionately with the magnitude of the error signal and inversely with the rate of change of the controlled variable. That this will give the proportional part of the control is easily seen. The provision of the integral action is not so obvious.

It has been mentioned that in a conventional controller having a separate integral channel, the integral channel increases gain for very slowly changing signals, but contributes no gain change for rapidly varying signals. In this invention the overall controller gain is high at d.c. or low frequency, and is reduced to a lower value as the rate of change of the controlled variable increases.

The embodiments of Figures 1 and 2 provide a response which resembles the overall frequency response of a proportional plus reset controller. However, instead of providing high gain at low frequencies by means of separate integral channel, the desired characteristic is obtained by leaving the gain unaffected at lower frequencies and decreasing gain at high frequencies. For example, a high proportional gain setting is selected which gives the desired low frequency response. This provides the desired small offset with different loads on the system, but would normally introduce instabilities into the system. This problem is eliminated in the described embodiments of this invention by sampling the error or controlled variable signal for frequencies which, if allowed to operate on the controller, would introduce instabilities. If these frequencies are present, the gain of the controller is suitably reduced. In general, the higher the frequency present, the lower the gain which will hold the system stable.

The overall control action of the system is quite similar to that of the conventional proportional plus reset controller despite the fact that there is no "integral channel" or "integral action" during those periods when the error signal includes a low frequency component.

The first embodiment of this invention is shown in Figure 1. A transducer 1, such as a thermocouple, generates a signal representing the value of the controlled variable. Transmitter 2 has input terminals 3 energized by the signal from transducer 1. The value of the controlled variable is represented by a 4-20 ma, output signal at output terminal 4.

A set point 5 having an output terminal 6, provides a 4-20 ma. output signal which represents the desired value for the controlled variable.

The signal representing the controlled variable and the signal representing the set point are applied to first input 7 and second input 8, respectively, of summing means 9. Output terminal 10 of summing means 9 provides a signal representing the deviation of the controlled variable from the desired value. The deviation, or error signal, is applied to input terminal 11 of controller amplifier 12. The output signal from amplifier 12 appears at terminal 13 from which a lead 14 conveys it to an actuator and valve or like device not shown in the process being controlled.

The gain of amplifier 12 is adjusted by manipulating the value of feedback resistor 15. Increasing the value of resistor 15 increases the gain of amplifier 12, and decreasing the value of resistor 15 decreases the gain. Actuator 16 is operative to control the value of feedback resistor 15 in direct proportion to the signal applied to terminal 17. This signal is proportional to the term G in the equation previously described.

Actuator 16 may be any suitable actuator capable of providing for example mechanical action to vary the value of feedback resistor 15. Where high speed response is not required, actuator 16 and resistor 15 could take the form of a servo-driven potentiometer. Another satisfactory form would be a radiation-sensitive resistance such as a photoconductor for feedback resistor 15 and in a radiation source such as a light bulb for actuator 16. In this case it would be necessary to invert the signal applied to input terminal 17.

A wide variety of devices are acceptable for the combination of resistor 15 and actuator 16, the choice being made according to cost, required speed of response and other such considerations.

Generation of the gain control signal at terminal 17 is accomplished by means of a signal comparison means such as differential amplifier 18, having first and second input terminals 19 and 20.

First input terminal 19 is connected to output terminal 10 of summing means 9. Amplifier 18 operates to provide an output signal at terminal 17 which varies in direct proportion to the error signal $(x-x_0)$ at first input terminal 19. The output signal at terminal 17 is further responsive to, and varies inversely with, the signal at second input terminal 20. Putting it another way, amplifier 18 operates as a signal comparison means to provide an output signal at terminal 17 which varies in accordance with the difference between the input signals at terminals 19 and 20. This being the case, the requirement for a gain signal representing the relationship $R\frac{(x-x_0)}{\frac{dx}{dt}}$ can be satisfied by applying a signal representing dx/dt to second input terminal 20.

In some applications the nature of the controlled system is such that the signal representative of dx/dt will be readily available and may be applied directly to terminal 20. In most situations this is not the case and some means for deriving the representation of dx/dt must be provided. While the derivation of a signal which exactly represents dx/dt is rather difficult and frequently requires complex circuitry, it has been found that a simple circuit provides a satisfactory approximation.

The use of high pass filter 21 and rectifier-integrator 22 between the controlled variable signal at terminal 4 and second input 20, results in a control signal at second input 20 which is representative of the high frequency components in the signal from the controlled variable. The relationship between the rectified and integrated high frequency components and the rate of change of the controlled variable dx/dt is not exact, but it has been found that the use of the approximation provides good control action. The action of integrator 22 is not to be confused with the integrator used in conventional proportional plus integral controllers. The integrator has a short time constant and is easily constructed from small inexpensive components. It can be seen that high pass filter 21 and integrator 22 operate to determine the energy content of the controlled variable signal within the band pass of the filter. Since a rapidly varying signal from the controlled variable will have substantial energy in the range of frequencies passed by the filter, the signal at input terminal 20 will be large. The time constant of integrator 22 will be quite short, serving only to provide a smoothed signal to input terminal 20. The actual value of dx/dt would also be large in this case.

The gain control signal also requires the introducion of R, commonly termed the reset rate in repeats per minute. This term is represented in the relationship of the actuator gain in response to the signal at terminal 17, the gain of differential amplifier 18 and the change in resistance 15 in response to the output of actuator 16.

If desired, input terminal 23 of high pass filter 21 may be removed from terminal 4 and connected to the output of summing means 9 at terminal 10. Connection at this point allows the controller to modify the abrupt nature of a change in the position of set point 5. A manual adjustment of set point 5 produces a high frequency signal at terminal 10 which would pass through filter 21 to momentarily reduce the gain of amplifier 12 and allow the system to respond to the set point change in a more gradual fashion.

The complete derivation of the gain control signal requires an additional term K which represents a minimum gain setting when the other term approaches zero. This may be introduced by the potentiometer 24 connected in series with the feedback resistor 15. Another satisfactory way of establishing a minimum gain value includes mechanical stops on actuator 17 which limit the value of resistance 15 at the low end.

In the system of Figure 2, high pass filter 21, integrator 22 and differential amplifier 18 function in the same manner as in the system of Figure 1; however, the functions of actuator 16 and variable resistor 15 are performed by analog to digital converter 25, digital actuator 26 and resistor network 27. In this embodiment the 4-20 ma. output signal from differential amplifier 18 is converted to digital form by analog to digital converter 25. The signals at output terminal 28 of analog to digital converter 25 may be in any satisfactorydigital code. Digital actuator 26 operates in response to the signal at output terminal 28 to open or close selected switches 27a—27e in series with individual resistors 27g—27k of resistor network 27. The actuator 26 operates to open and close the selected switches 27a—27e to provide a high value of feedback resistance for large digital outputs and low values of feedback resistance for low digital outputs. A resistor 27f may be permanently connected in the feedback circuit to establish a minimum gain value.

While the embodiments of Figures 1 and 2 utilize analog circuits for the analysis of the error signal as to magnitude and frequency, this analysis may also be performed by suitable digital means. In the system of Figure 3, an analog to digital converter 29 provides a digital value at terminal 30 which represents the analog error signal. This digital value is then evaluated by computer 31 for magnitude, and, in combination with readings taken previously, the computer may then evaluate the term dx/dt. The derivation of the gain control signal G according to the previously discussed equation is accomplished by straightforward digital computations. When these computations are complete, appropriate signals are supplied to digital actuator 26 for connecting in the desired feedback resistance.

Figure 4 illustrates the relationship between the filter characteristic and the gain of amplifier 12. For signals having essentially no components above the break point of the filter, gain is not reduced by the operation of differential amplifier 18 and will remain at a value established by the signal at input 19. As the signal applied to filter 21 contains increasing high frequency energy, the output from the filter 21 and integrator 22 increases to cause a corresponding reduction in gain of amplifier 12.

In some controlled systems, the random higher frequency noise which exists in the signal representing the controlled variable may be such as to require filter 21 to have an upper limit on the pass band as shown in Figure 4.

WHAT WE CLAIM IS:—

1. Method of adaptive closed loop control in which controller gain is varied in accordance with a gain control signal derived by subtracting a second component from a first component, the first component being or representing the error signal and the second component increasing with increasing rate of change of the error signal or the controlled variable, whereby the controller gain is varied in direct proportion with the magnitude of the error signal and in inverse proportion with the rate of change of the error signal or the controlled variable so as to give proportional plus integral control.

2. Adaptive closed loop control system having a controller whose gain is varied in accordance with a gain control signal generated by error modification means, said error modification means generating said gain control signal by subtracting a second component from a first component, the first component being or representing the error signal and the second component increasing with increasing rate of change of the error signal or the controlled variable, whereby the gain control signal varies the controller gain in direct proportion with the magnitude of the error signal and in inverse proportion with the rate of change of the error signal or the controlled variable to cause the system to provide proportional plus integral control.

3. A system as claimed in claim 2, in which said error modifications means comprises a differential amplifier one of whose inputs is connected to receive the error signal and the other of whose inputs is connected via an integrating circuit to a high pass filter which receives the error signal or a signal representing the controlled variable, the high pass filter being designed to pass high frequency components occurring in the error signal or the signal representing the controlled variable, and the integrating circuit being designed to produce a rectified integrated signal from the filter output for the differential amplifier.

4. A system as claimed in claim 3 in which the integrating circuit comprises a capacitor connected via a resistor and diode to the high pass filter, the high frequency components causing the capacitor to charge, and said other input of the differential amplifier being responsive to the voltage developed across the capacitor.

5. A system as claimed in claim 3 or 4 including means for varying a set point for the system representing the desired value of the controlled variable, adjustment of said means to vary the set point causing high frequency components in the error signal and the controlled variable signal.

6. A system as claimed in any of claims 2 to 5 in which the controller is an amplifier whose gain is controlled in accordance with the magnitude of feedback resistance connected across the amplifier, the system further including an actuator responsive to said gain control signal to vary said feedback resistance.

7. A system as claimed in claim 6 in which said feedback resistance is provided by a variable potentiometer adjusted by said actuator.

8. A system as claimed in claim 6 in which said feedback resistance is provided by a plurality of feedback resistors which can be selectively connected in the feedback circuit by means of switches operated by said actuator.

9. A system as claimed in claim 2 in which said error modification means comprises an analogue-to-digital converter feeding a digital computer which is programmed to compute and generate said gain control signal.

10. Method of adaptive closed loop control substantially as described with reference to Figure 1 of the accompanying drawing.

11. Method of adaptive closed loop control substantially as described with reference to Figure 2 of the accompanying drawing.

12. Method of adaptive closed loop control substantially as described with reference to Figure 3 of the accompanying drawing.

13. Adaptive closed loop control system substantially as described with reference to Figure 1 of the accompanying drawing.

14. Adaptive closed loop control system substantially as described with reference to Figure 2 of the accompanying drawing.

15. Adaptive closed loop control system substantially as described with reference to Figure 4 of the accompanying drawing.

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